Quantum Mechanics without Nonlocality

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Abstract

We argue that quantum nonlocality of entangled states is not an actual phenomenon. It appears in quantum mechanics as a consequence of the inconsistency of its superposition principle with the corpuscular properties of a quantum particle. In the existing form, this principle does not distinguish between macroscopically distinct states of a particle and their superpositions: it implies introducing observables for a particle, even if it is in an entangled state. However, a particle cannot take part simultaneously in two or more alternative macroscopically distinct sub-processes. Thus, calculating the expectation values of the one-particle's observables, for entangled states, is physically meaningless: Born's formula is not applicable to such states. The same concerns the entangled states of compound quantum systems. In the *existing* quantum mechanics, introducing Bell's inequalities is fully legal. However, these inequalities imply averaging over an entangled state, and, hence, they have no basis for their clear physical interpretation. Experiments to confirm the violation of Bell's inequalities do not prove the existence of nonlocality in microcosm. They confirm only that correlations introduced in the existing theory of entangled states have no physical sense, for they contradict special relativity.

1 Introduction

As is well known, quantum nonlocality of entangled states is, perhaps, the most intriguing question to arise in the modern physics. Quantum theory [1,2] and experiment [3] say that in the case of entangled states there should be nonzero correlations between two space-like separated events. From the practical point of view, this property of entangled states is one of the most desirable findings of quantum mechanics. For it opens unusual perspectives in developing the various forms of information technology (see, e.g., [4]).

However, despite these opportunities, the phenomenon of quantum nonlocality has remained as an undesirable "guest" in the modern physics. As is known (see, e.g., [5,6,7,8]), Einstein waged a relentless struggle against this prediction of quantum mechanics. For it contradicts the principles of special relativity, and, as a result, it violates the continuity in science.

To reconcile quantum mechanics with special relativity, Heisenberg was perhaps first (see [9] and [5]) who stated that quantum nonlocality "... is not in conflict with the postulates of the theory of relativity." This idea was later developed by Bell [10] (see also a quote in [5]): having proved his famous theorem, Bell was disturbed with his own result. In order to smooth the contradiction between quantum mechanics and special relativity, Bell suggested that nonzero correlations between space-like separated events do not at all mean the existence of a superluminal signalling between such two events (see also [9]). As is now accepted in all the so-called non-signalling theories (see, e.g., [11]), quantum nonlocality is an *uncontrollable phenomenon* [12].

However, one should recognize that such terms as 'nonzero non-signalling correlations' and 'uncontrollable phenomenon' are too ambiguous. They do not explain the phenomenon of quantum nonlocality (see also [13]). These terms themselves need explanation.

It should be stressed that Bell himself considered the 'non-signalling' explanation as a hard choice. He wrote (quoted from [5]): Do we then have to fall back on no signaling faster than light as the expression of the fundamental causal structure of contemporary theoretical physics? That is hard for me to accept. For one thing we have lost the idea that correlations can be explained, or at least this idea awaits reformulation. More importantly, the no signaling notion rests on concepts which are desperately vague, or vaguely applicable." So, Bell says in fact that the 'non-signalling' explanation of nonzero correlations between space-like separated events makes meaningless the very notion of 'correlations'.

We agree entirely with these doubts. All the known 'no-signalling' explanations are based on the implicit assumption that the principles of quantum mechanics are mutually consistent. However, this is not the case. To prove this statement, we address the quantum problem of a completed scattering of a particle on a static one-dimensional (1D) potential barrier (see [14]). In this case the analysis of quantum nonlocality is essentially simpler than for compound systems considered in the 'no-go' theorems, where there are fundamental problems associated with multipartite quantum measurements (see, e.g. [15]).

2 On the phenomenon of quantum nonlocality in the existing model of a 1D completed scattering

As is known (see reviews [16,17,18,19,20,21,22], during the last three decades this quantum phenomenon have been in the focus of the intensive debate on the so-called tunneling time problem, without reaching any consensus.

It should be noted that solving this problem have not been aimed to prove the existence of quantum nonlocality. At the same time the latter has arisen in all the existing approaches to the tunneling time problem. The well-known group- and dwell-time concepts [16,23,24,25,26] are not exceptions. Like other concepts they lead to the unrealistic tunneling times for a scattering particle. As it has turned out, for a transmitted particle the group and dwell times may be anomalously short or even negative by value.

It is important to stress that all these approaches, like the 'no-go' theorems, do not doubt a consistency of the quantum-mechanical principles. And, like the 'no-go' theorems, they in fact prove that nonlocality is an inherent property of conventional quantum mechanics.

However, just the main peculiarity of the existing quantum-mechanical model of a 1D completed scattering is that it is inconsistent (in details, this question is studied in [14]). This fact can be demonstrated, for example, in the case of the Bohmian mechanics. Indeed, the Bohmian model of the process (see [27]) predicts that the fate of an incident particle (to be transmitted or to be reflected by the barrier) depends on the coordinate of its starting point. However, this property is evident to contradict the main principles of quantum mechanics, since a starting particle should have both the possibilities, irrespective of the location of its starting point.

It is evident that this peculiarity of the existing Bohmian model is closely connected to spatial nonlocality. Indeed, the position of a critical spatial point to separate the starting regions of to-be-transmitted and to-be-reflected particles depends on the shape of the potential barrier (though the barrier is located at a considerable distance from the particle's source). Thus, the "causal" trajectories of transmitted and reflected particles, introduced in the Bohmian mechanics, are, in fact, non-causal: they are ill-defined.

So, in the Bohmian model of a 1D completed scattering, nonlocality and inconsistency accompany each other. However, this situation is common for all the known approaches to deal with a 1D completed scattering (see [14] and references therein). Our analysis shows that quantum nonlocality to arise in the existing model of a 1D completed scattering results from the inconsistency of the superposition principle with the corpuscular properties of a particle.

3 A 1D completed scattering as an entanglement of transmission and reflection

In [14]) we have presented a new model of a 1D completed scattering for a particle impinging a symmetrical potential barrier from the left. We show that, for a given potential and initial state of a particle, the (full) wave function $\psi_{full}(x; E)$ to describe this process, for a particle with a given energy E, can be uniquely presented in the form,

$$\psi_{full}(x; E) = \psi_{ref}(x; E) + \psi_{tr}(x; E),$$

where $\psi_{ref}(x; E)$ and $\psi_{tr}(x; E)$ are solutions to the stationary Schrödinger equation. They are such that allow us to retrace the time evolution of the (to-be-)transmitted and (to-be-)reflected *subensembles* of particles at all stages of scattering.

As it has been shown in [14], for any symmetric potential, $\psi_{ref}(x; E)$ is an odd function with respect to the midpoint x_c of the barrier region; i.e., for any value of E we have $\psi_{ref}(x_c; E) = 0$. This means that particles impinging the barrier from the left do not enter the region $x > x_c$.

Let the wave function to describe the subensemble of such particles be denoted $\tilde{\psi}_{ref}(x; E)$. Then

$$\tilde{\psi}_{ref}(x; E) \equiv \psi_{ref}(x; E) \quad for \quad x \leq x_c; \quad \tilde{\psi}_{ref}(x; E) \equiv 0 \quad for \quad x \geq x_c. \tag{1}$$

Correspondingly, the function $\tilde{\psi}_{tr}(x; E)$ -

$$\tilde{\psi}_{tr}(x; E) = \psi_{full}(x; E) - \tilde{\psi}_{ref}(x; E)$$

- which can be presented also as

$$\tilde{\psi}_{tr}(x; E) \equiv \psi_{tr}(x; E) \, for \, x \leq x_c; \quad \tilde{\psi}_{tr}(x; E) \equiv \psi_{full}(x; E) \, for \, x \geq x_c, \tag{2}$$

describes the subensemble of particles with energy E, which impinges the barrier from the left and then passes through the barrier, without reflection and without violating the continuity equation at the midpoint x_c. This property of $\tilde{\psi}_{tr}(x; E)$ results from the fact that the solutions $\psi_{tr}(x; E)$ and $\psi_{full}(x; E)$ have the same probability current density and, besides, $\psi_{tr}(x_c; E) = \psi_{full}(x_c; E)$.

It is evident that the wave packets $\tilde{\psi}_{tr}(x, t)$ and $\tilde{\psi}_{ref}(x, t)$ formed from $\tilde{\psi}_{tr}(x; E)$ and $\tilde{\psi}_{ref}(x; e)$, respectively, obey the time-dependent Schrödinger equation

everywhere except for the point x_c. However, the continuity equation is not violated at this point. So that both the wave packets, being everywhere continuous at any instant of time, evolve in time with constant norms.

By our approach, namely $\tilde{\psi}_{tr}(x,t)$ and $\tilde{\psi}_{ref}(x,t)$ (each possesses one incoming and one outgoing packet) describe the time evolution of the (to-be-)transmitted and (to-be-)reflected subensembles of particles at all stages of scattering. In this case,

$$\psi_{full}(x,t) = \psi_{tr}(x,t) + \psi_{ref}(x,t) = \tilde{\psi}_{tr}(x,t) + \tilde{\psi}_{ref}(x,t),$$

where $\psi_{tr}(x,t)$ and $\psi_{ref}(x,t)$ are the wave packets formed from the solutions $\psi_{ref}(x;E)$ and $\psi_{tr}(x;E)$.

Thus, the superposition of two solutions to the Schrödinger equation, $\psi_{tr}(x,t)$ and $\psi_{ref}(x,t)$, is equivalent to that of $\tilde{\psi}_{tr}(x,t)$ and $\tilde{\psi}_{ref}(x,t)$ to describe the sub-processes, transmission and reflection. Since these sub-processes are macroscopically distinct at the final stage of a 1D completed scattering, the state of a particle to take a part in a 1D completed scattering should be considered as an entangled one. This means, in particular, that the quantum nonlocality to arise in the previous model of a 1D completed scattering is just that inherent to entangled states.

At this point it is important to stress that transmission and reflection are not independent quantum processes: they are two alternatives to arise for a particle in the same scattering problem. So that it is not surprising that $\tilde{\psi}_{tr}(x,t)$ and $\tilde{\psi}_{ref}(x,t)$ to describe these sub-processes are not *independent* solutions to the Schrödinger equation. As is seen, they can be considered only together, as constituent parts of the same entangled state $\psi_{full}(x,t)$.

The study of temporal aspects of a 1D completed scattering, carried out on the basis of $\tilde{\psi}_{tr}(x,t)$ and $\tilde{\psi}_{ref}(x,t)$ (see [14]), has shown that the behavior of both the sub-processes does not exhibit quantum nonlocality. They evolve in time without superluminal velocities.

Besides, it has been stated that only the dwell time can be considered as a measure of the time spent, on the average, by particles of either subensemble in the barrier region. This characteristic time can be measured with the help of the Larmor clock, without demolishing the scattering process. It is important to stress here that the probability fields for transmission and reflection, being superimposed, do not influence each other.

As regards the group and other characteristic times (which cannot be measured with the Larmor clock), they seem to have no physical sense when a particle is in entangled state. By our approach, none point of the wave packet can

be used as a representative of a particle (in an entangled state) in timing its motion in the barrier region. It says that it is impossible, with the help of the Larmor clock, to track the motion of any point of a moving wave packet.

One remark should be made also in regard to the Bohmian quantum mechanics. As is seen, our model in fact implies the introduction of two individual sets of the causal trajectories for a particle, both for transmission and reflection. In this case, in a full accordance with the quantum-mechanical principles, each starting particle has two possibilities, irrespective of the coordinate of its starting point.

4   The wave-particle duality and superposition-decomposition principle for entangled states

By our approach, the above decomposition of the entangled one-particle's state is the only way to explain the properties of a 1D completed scattering, since all one-particle's observables can be introduced only for unentangled one-particle's states, i.e., for transmission and reflection. As regards any entangled state of a scattering particle, introduction of observables, which would be common for the transmitted and reflected subensembles of particles, has no physical sense.

Indeed, a particle, as an indivisible object, cannot simultaneously take part in two (or several) macroscopically distinct processes. This means that its 'quantum trajectory', which must be non-divaricate, can be presented only by an unentangled time-dependent state. Only such state may serve as a counterpart to the classical one-particle trajectory. All quantum-mechanical rules (including Born's interpretation of the squared modulus of the wave function as well as Born's rule of calculating the expectation values of observables) have physical sense only for unentangled ("non-dendritic") time-dependent states.

This also concerns calculating the correlations between two events for compound quantum systems. As is known, such calculations imply averaging over the state of a system. By our approach, such averaging is meaningful only if both these events belong to the same "non-dendritic quantum many-particle trajectory", i.e., if the system is in an unentangled time-dependent state.

So, the quantum-mechanical superposition principle must distinguish, on the conceptual level, macroscopically distinct states and their superpositions. In other words, it should distinguish unentangled and entangled quantum states. All observables can be introduced only for unentangled states.

By our approach, if some pure entangled one-particle's state implies the motion

of a particle along a macroscopically dendritic way, hence we deal with an entangled state. And, in order to explain the motion of a particle along this way, we have to decompose the entangled state into unentangled (elementary) ones which do not contain macroscopically distinct divarications for a moving particle.

4.1 Conclusion

So, by our approach, quantum nonlocality of entangled states is an artifact of the existing quantum theory. It appears in quantum mechanics due to the inconsistency of its superposition principle with the corpuscular properties of a particle. This principle should be corrected.

Namely, (1) it must distinguish, on the conceptual level, macroscopically distinct states and their superpositions; (2) it must forbid introducing observables for entangled states; (3) it must require decomposing entangled states into the set of unentangled ones, when such a set has not yet been found.

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